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MEASUREMENT OF AIR TEMPERATURE FLUCTUATIONS WITH THERMOCOUPLES

By

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ABSTRACT

Equations for determining the radiant heating and time constant of small thermocouples used for air temperature measurement are presented. Calculated and measured values are compared for 0.0025, 0.0127, and 0.0508 cm diameter copper-constantan thermocouples exposed to direct sunlight. The largest thermocouple gives measured temperatures that are approximately 1.3C higher than air temperature, and the smallest thermocouple reads about 0.3C above air temperature when they are exposed to direct solar radiation. In direct sunlight and for a range of wind speed of 100 to 500 cm sec^{-1} the temperature is reduced by 0.8 and 0.1C for the largest and smallest thermocouples, respectively.

The effects of two types of aspirated thermoshields on temperature fluctuations measured inside the shield with the 0.0025 cm thermocouples were determined. Thermoshield design was shown to be critical in temperature fluctuation measurement.

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INTRODUCTION

Fine-wire thermocouples have been used for measuring air temperature fluctuations in a number of studies. In some studies (e.g., House, et al., 1960) it is assumed that radiant heating errors on very small thermocouples are negligible. However, Swinbank (1951) calculates that the mean temperature measured by a 0.0025 cm diameter thermocouple exposed to direct sunlight could be 0.13C too high when the wind speed is 200 cm sec^{-1}. An objective of this study was to measure radiant heating errors for several sizes of thermocouple and compare the values obtained with calculated values.

Since fine-wire thermocouples are used for measuring air temperature fluctuations, it would be helpful to be able to calculate time constants for thermocouples of various sizes in terms of wind speed and wire diameter. Also, if the thermocouples are used inside aspirated radiation shields in order to make accurate mean temperature measurements, one should know what effect, if any, aspiration has on the measurement of temperature fluctuations. A further objective of this study, therefore, was to compare experimentally determined time constants with values calculated from heat transfer equations and to determine the effects of aspiration on measured temperature fluctuations.

RADIANT HEATING EFFECTS

The temperature of a thermocouple is determined by the rates of convective and radiative heat transfer at its surface. Ideally, the convective heat transfer should be much larger than the radiative heat transfer so that the thermocouple temperature accurately represents air temperature. To determine the error in air temperature measurement due to radiation, the energy balance for a thermocouple (similar to development by Gates, 1965) can be written in terms of ΔT, the difference between thermocouple and air temperatures. If the thermocouple is assumed to be a horizontally oriented, infinite cylinder with the top half radiating to the sky and the bottom half radiating to the ground, then

$$\Delta T = \frac{\varepsilon_s(1 + \frac{\pi\alpha}{2})\, R_s + \pi\varepsilon_L\,(\frac{R_a + R_g}{2} - \sigma T^4)}{h} \qquad (1)$$

where h is the average convective conductance, ε_s and ε_L are short- and long-wave emissivities of the thermocouple, α is the albedo, R_s is the short-wave incoming radiation, R_g is the long-wave radiation from the ground, R_a is the long-wave atmospheric radiation,

σ is the Stephan-Boltzmann constant, and T is the thermocouple temperature.

Average convective conductance for infinite cylinders in forced convection can be approximated (Kreith, 1965, p. 411) by

$$h = \frac{Kk}{D} \left(\frac{V\ D}{\nu}\right)^n \qquad (2)$$

where D is the wire diameter, V the wind speed, k the heat conductivity for air, and ν the kinematic viscosity of air. K and n are empirically determined dimensionless constants (Kreith, 1965, p. 411). Appropriate values for K and n at V = 300 cm sec^{-1} are given in Table I. Substituting Eq. (2) into Eq. (1) yields the wire diameter and wind speed dependence of ΔT:

$$\Delta T = \left[\varepsilon_s \left(1 + \frac{\pi\alpha}{2}\right) R_s + \pi\varepsilon_L\left(\frac{R_a + R_g}{2} - \sigma T^4\right)\right] \frac{D}{Kk} \left(\frac{\nu}{V\ D}\right)^n . \qquad (3)$$

Representative values of the parameters in Eq. (3) for a copper-constantan thermocouple suspended above a dry, desert surface at noon on a clear summer day are α = 0.25 (Sellers, 1965, p. 21), ε_s = 0.25, ε_L = 0.5 (Handbook of Chem. and Phys.), R_a = 0.008 cal cm^{-2} sec^{-1} (Gates, 1965), R_g = 0.015 cal cm^{-2} sec^{-1}, R_s = 0.022 cal cm^{-2} sec^{-1}, T = 300K, and V = 300 cm sec^{-1} (representative of average experimental conditions to be described later). Values of ΔT calculated using these numbers are presented in Table I.

Table I. Comparison of Measured and Calculated Values of ΔT and τ and values of K and n for V = 300 cm sec^{-1}

D-Cm	K	n	ΔT-C		τ-sec	
			Calculated	Measured	Calculated	Measured
0.0025	0.821	0.385	0.24	0.30	0.014	0.028
0.0127	0.821	0.385	0.65	0.75	0.19	0.35
0.0508	0.615	0.466	1.4	1.3	1.85	1.7

Experimental measurements of ΔT were obtained by recording outputs from 0.0508, 0.0127, and 0.0025 cm diameter thermocouples and comparing them to the temperature measured with a thermocouple mounted in an MRI[1] model 801 aspirated thermoshield. The 0.0127 and 0.0025 cm thermocouple junctions were welded using a technique described by Campbell et al. (1968), modified to produce small junctions. The largest thermocouple was welded using a commercially available thermocouple welder. It was assumed that the thermocouple inside the aspirated thermoshield measured true air temperature since the manufacturer specifies a radiant heating error of less than 0.1C. The thermocouples and an anemometer were located at a height of 8 m above a dry desert surface at White Sands Missile Range, New Mexico. Temperatures and wind speed were recorded at 1 sec intervals between 1045 and 1215 hrs Mountain Daylight Time (MDT) on 16 May 1969, a cloudless day. The one-second temperature readings were averaged over five-minute intervals and the five-minute means were plotted to show the effect of radiant heating on the mean temperature measured by the thermocouples (Fig. 1). The measured R_S, obtained using an Eppley pyrheliometer, was 0.022 cal cm^{-2} sec^{-1} at noon.

From 1045 to 1115 hrs the thermocouples were shaded from direct sunlight by the mast. During this time the readings of the smallest thermocouple were about the same as those of the standard (Fig. 1). The larger thermocouples gave temperatures above the standard. Between 1115 and 1215 hrs all of the thermocouples were exposed to direct sunlight. During this time, all of the thermocouples gave readings above true air temperature. The average of the differences between the temperature measured by each of the unshielded thermocouples in bright sunlight and that measured by the standard is shown in Table I. The average experimental values of ΔT agree quite well with the values calculated using Eq. (3).

The ΔT for each of the five-minute means was plotted as a function of the mean wind speed for each five-minute period to show the effect of wind speed on ΔT (Fig. 2). Over the range of wind speeds shown, ΔT for the smallest thermocouple is quite insensitive to wind speed changes while ΔT for the largest thermocouple shows a rather large dependence on wind speed.

Time Constant of Thermocouples

The temperature response of an infinite cylinder to a step change in temperature is given by (Kreith, 1965, p. 129)

[1]Meteorology Research Inc., Altadena, California.

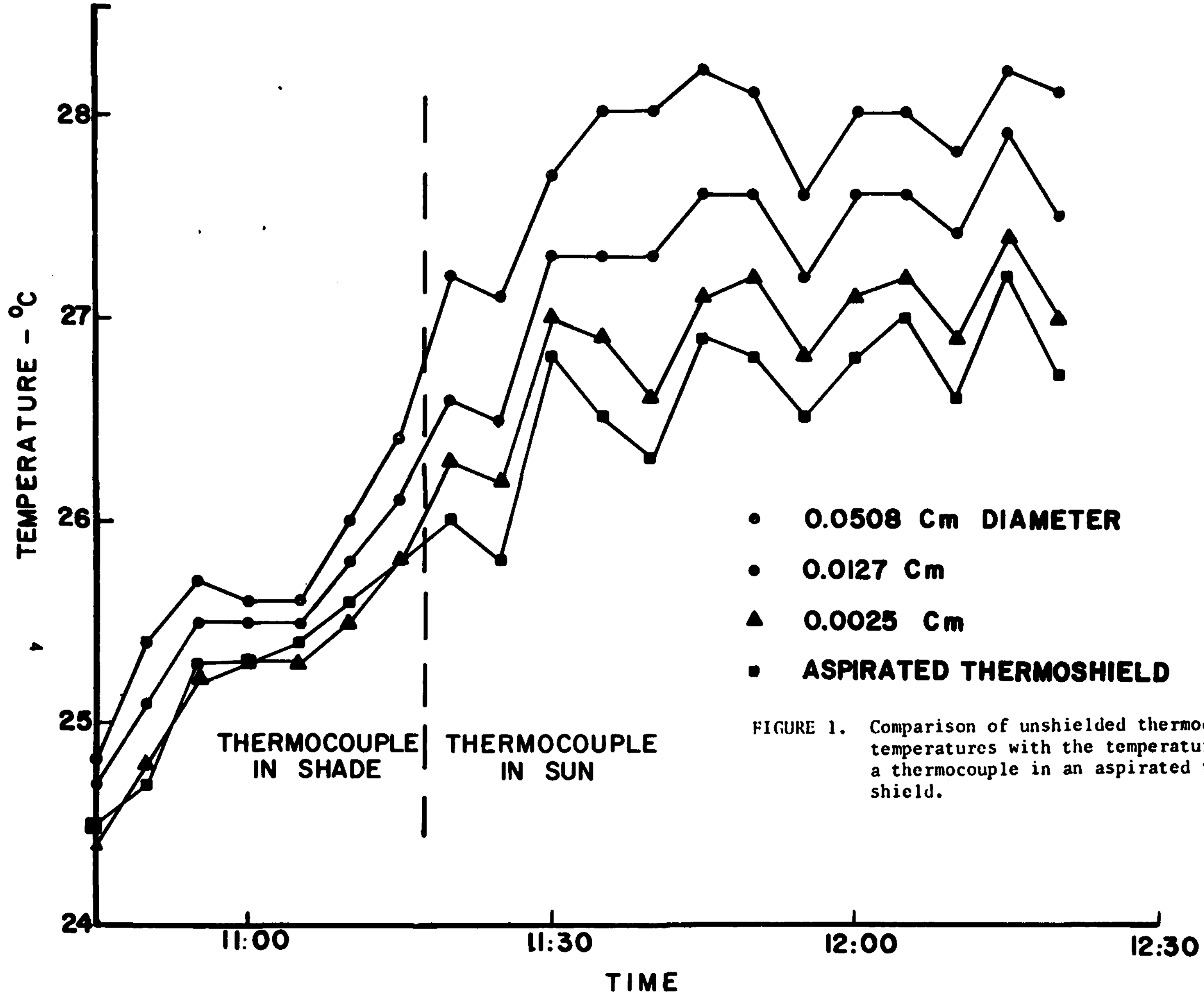

FIGURE 1. Comparison of unshielded thermocouple temperatures with the temperature of a thermocouple in an aspirated thermoshield.

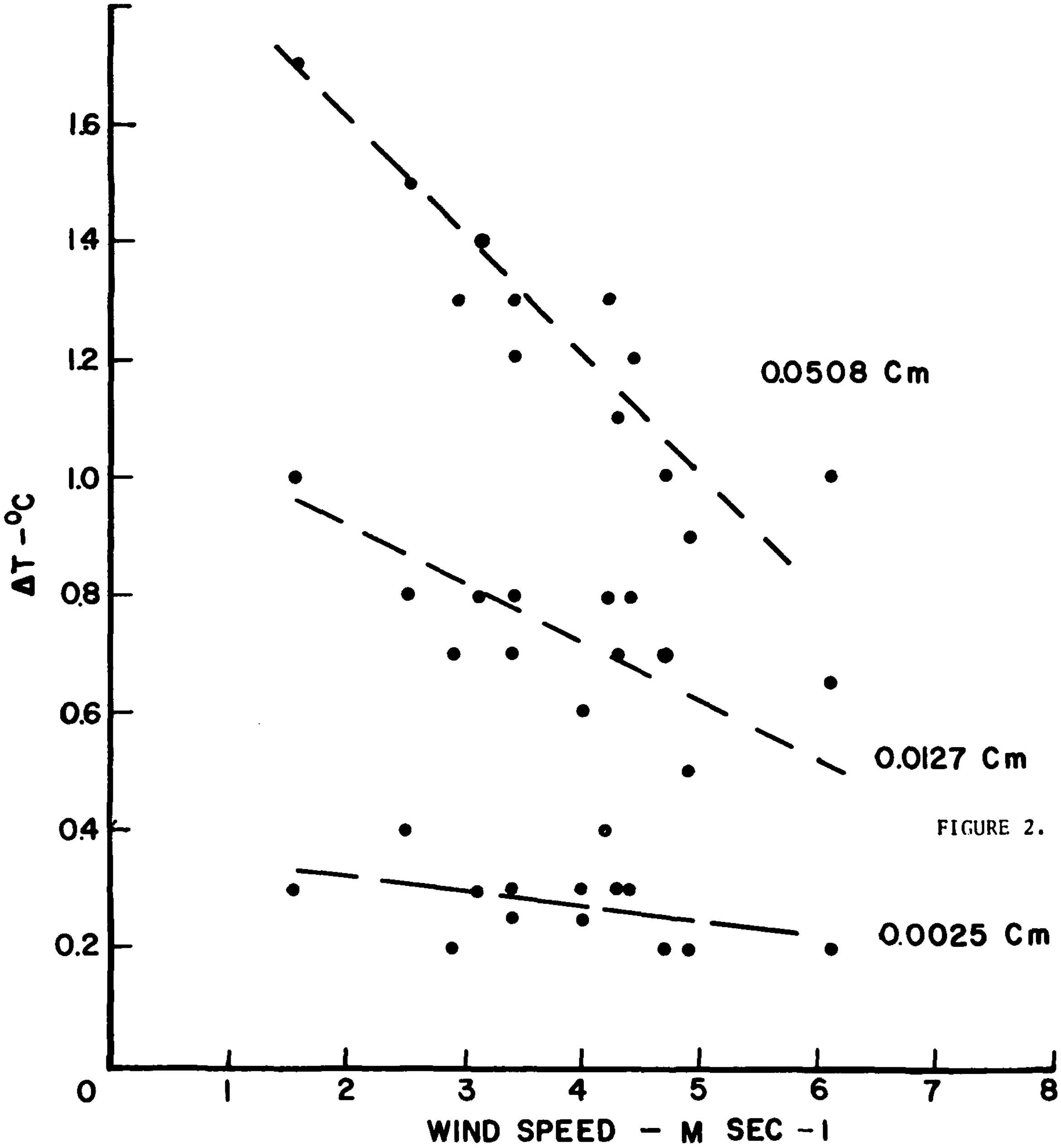

FIGURE 2. Effect of wind speed on radiant heating errors for three thermocouple sizes. Dashed curves are smoothed estimates of wind speed effects.

$$\frac{T - T_\infty}{T_o - T_\infty} = \exp\left(-\frac{4h\ t}{c\rho D}\right) \tag{4}$$

where T_o and T_∞ are the initial thermocouple temperature and the air temperature, c and ρ the average heat capacity and density of the thermocouple material, respectively, and t is the time. The time constant of the thermocouple (Kreith, 1965, p. 129)

$$\tau = \frac{c\rho D^2}{4Kk}\left(\frac{\nu}{V\ D}\right)^n \tag{5}$$

where h has been replaced from Eq. (2). Time constants calculated using Eq. (5) are shown in Table I. Values of τ were measured by heating the thermocouples to 10-15C above air temperature and recording their return to ambient temperature in a 300 cm sec^{-1} artificial wind. The agreement between calculated and experimental values is good (Table I).

Measurements With Aspirated Thermocouples

Figure 1 shows that ambient temperatures measured with thermocouples are likely to be affected by direct solar radiation unless the thermocouples are mounted inside aspirated thermoshields. The next question was what effect does aspiration have on temperature fluctuation measurements. To investigate this, thermocouples made from 0.0025 diameter wire were mounted in a Climet[2] Model B2826 and an MRI Model 801 aspirated radiation shield, and measurements of temperature fluctuations were made at a height of 2 m above the ground. Time of day and location were the same as for the previous experiment. The 2 m height was used rather than 8 m to give more rapid fluctuations. The outputs from these aspirated thermocouples as well as the unshielded 0.0025 and 0.0127 cm diameter thermocouples at the same height were compared using a multichannel oscillograph. The results are shown in Figure 3. Fluctuations measured by the thermocouple in the MRI shield closely resemble those measured with the smallest unshielded thermocouple. The trace for the larger unshielded thermocouple shows the filtering effect of the larger thermocouple mass, as expected.

The thermocouple in the Climet shield shows the same fluctuations but to a considerably reduced amplitude. The effect is attributed to mixing at the aspirator air intake because the amplitude reduction does not appear to depend on the frequency of the temperature fluctuations as is the case with filtering.

[2]Climet Instruments Inc., Sunnyvale, California.

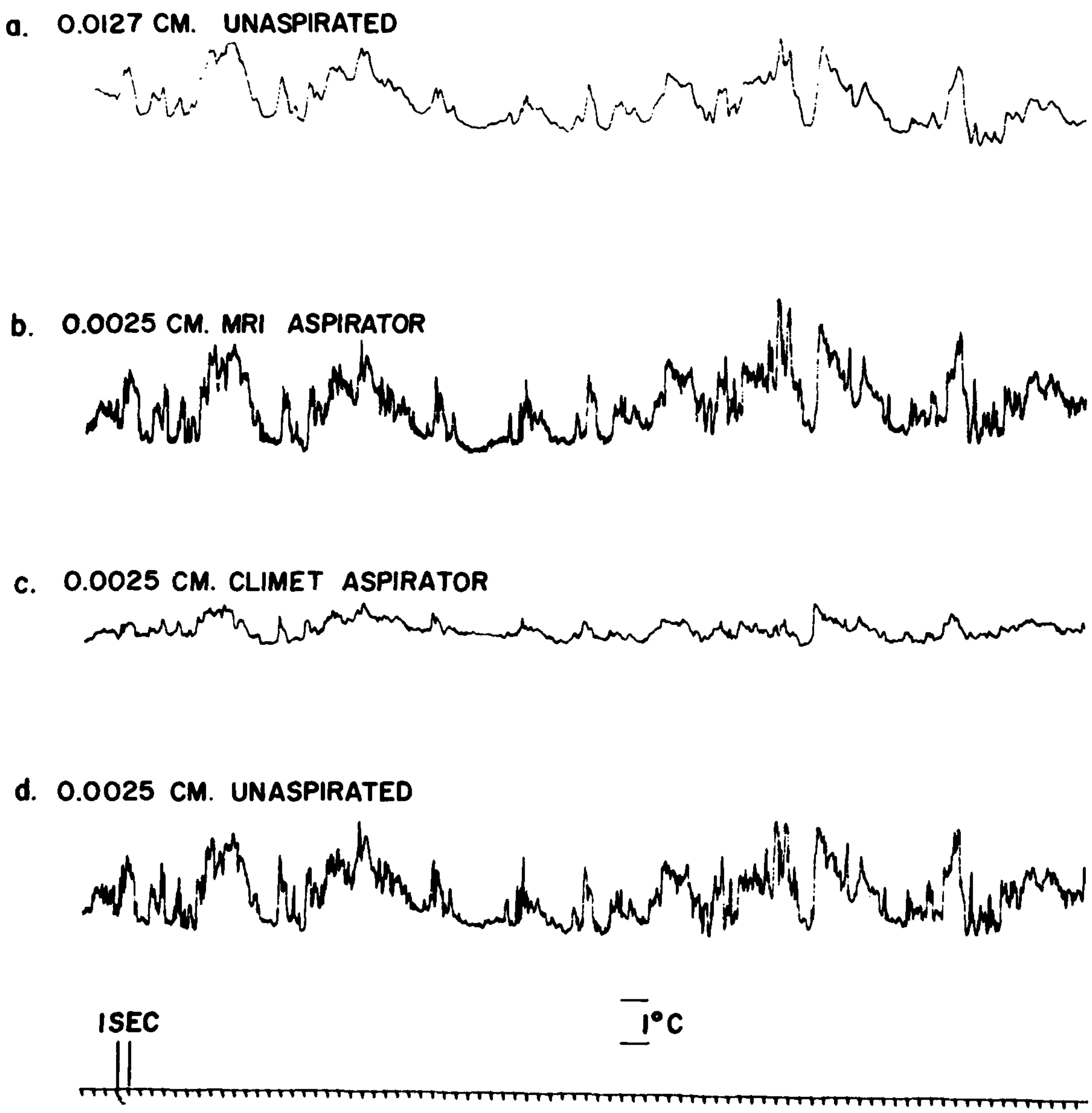

FIGURE 3. Comparison of temperature fluctuations measured with (a) 0.0127cm unshielded thermocouple and with 0.0025 cm thermocouples in (b) an MRI aspirator, (c) a Climet aspirator, and (d) no thermoshield.

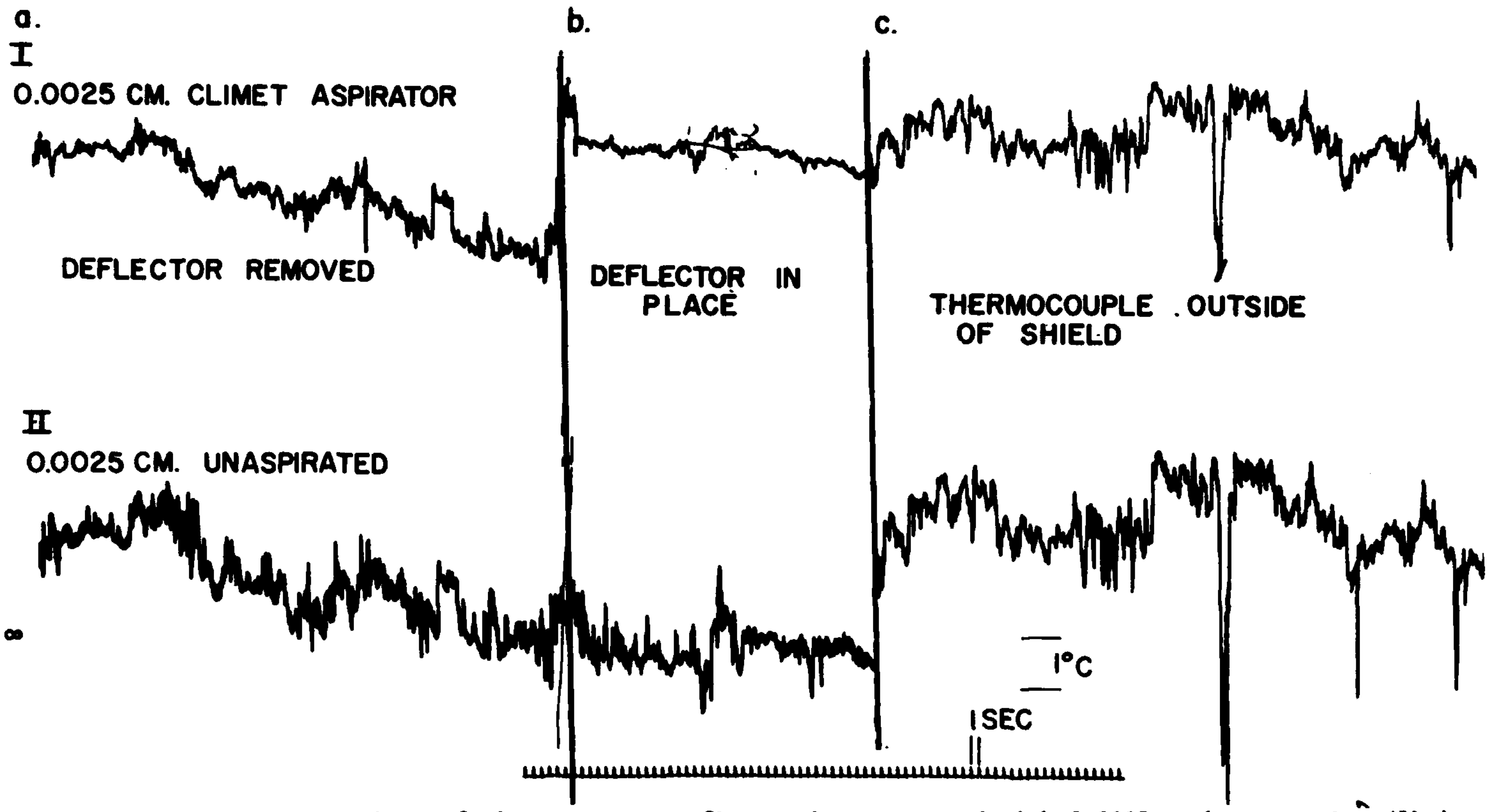

FIGURE 4. Comparison of air temperature fluctuations measured with 0.0025cm thermocouples (I) in a Climet aspirator and (II) unaspirated.
a. Radiation deflectors at air intake of Climet aspirator removed.
b. Deflectors replaced.
c. Both thermocouples unaspirated,

An additional comparison of fluctuations measured by the thermocouple in the Climet aspirator with those measured by an unaspirated thermocouple is shown in Figure 4. Note that with the radiation deflector removed from the aspirator air intake (Fig. 4a) the fluctuations measured by the aspirated thermocouple compare favorably with those measured by the unaspirated thermocouple. The amplitude of the fluctuations is slightly smaller for the aspirated thermocouple, but it is also slightly smaller when the thermocouple is outside the shield and unaspirated (Fig. 4c). This difference may be due to slight differences between thermocouples or recorder channels. A marked difference is observed, however (Fig. 4b), when the deflector is replaced.

CONCLUSIONS

Based on the analysis presented, it appears that reasonable estimates of radiation heating and thermocouple time constant can be obtained from the heat transfer equations presented here. Significant radiant heating occurs even with very small thermocouples when they are exposed to direct sunlight. Small diameter thermocouples will provide reasonable air temperature estimates if shielded from direct solar radiation. The design of aspirated radiation shields should be considered critical in determining the effect of the shield on measured temperature fluctuations.

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13. ABSTRACT

Equations for determining the radiant heating and time constant of small thermocouples used for air temperature measurement are presented. Calculated and measured values are compared for 0.0025, 0.0127, and 0.0508 cm diameter copper-constantan thermocouples exposed to direct sunlight. The largest thermocouple gives measured temperatures that are approximately 1.3C higher than air temperature, and the smallest thermocouple reads about 0.3C above air temperature when they are exposed to direct solar radiation. In direct sunlight and for a range of wind speed of 100 to 500 cm sec^{-1} the temperature is reduced by 0.8 and 0.1C for the largest and smallest thermocouples, respectively.

The effects of two types of aspirated thermoshields on temperature fluctuations measured inside the shield with the 0.0025 cm thermocouples were determined. Thermoshield design was shown to be critical in temperature fluctuation measurement.

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